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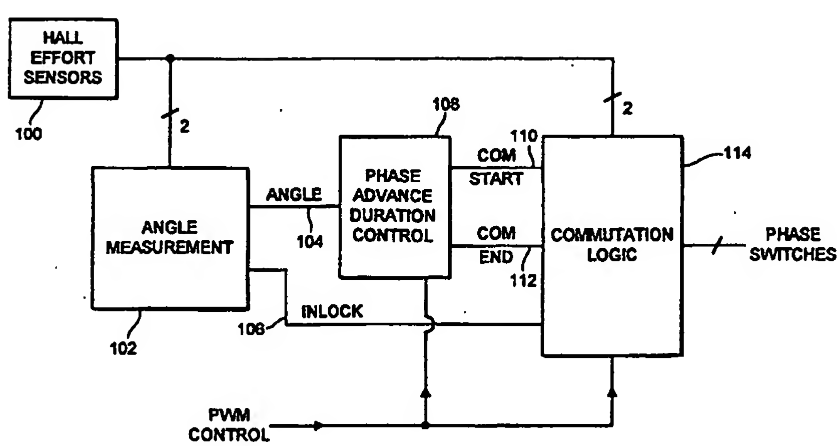

(57) Abstract

In a brushless dc motor controller having electronic switches to control the current flow in each phase of the motor, event sensors are used to detect certain positions of the magnet flux of the motor. These switches are turned on or off by outputs from a commutation circuit which decodes the outputs from the event sensors. Operation of these switches can be extended over a greater angular range by turning the switches on earlier and holding them on for longer in order to achieve a greater power output and efficiency from the motor. A Phase Resetting integrator is used to predict the angle between sensor events and this is compared to a start angle and an on angle which will be set for maximum power output. These comparisons are then used in a gated bistable circuit to generate the switched control signals.

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CONTROLLING BRUSHLESS DIRECT CURRENT MOTORS

This invention relates to the control of brushless direct current (dc) motors.

In order to establish torque in a brushless dc motor the current energising the windings of the motor must be applied in sympathy with the magnetic flux coupling to the motor winding being energised. To achieve the greatest torque from the motor, the winding current should be correctly phased with and in synchronism with the magnetic flux coupling to the winding.

For motors producing continuous torque more than one winding distributed over a complimentary pair of magnet poles is required. Each winding, which is also called a phase, is then sequentially energised with a bidirectional current using electronic switches.

It has been proposed, in order to reduce the number of switches, to use a 3 phase motor with the phases connected either in a Star or Delta configuration such that only 3 electrical connections are made to the motor. Thus only 6 switches connected in a 3 phase bridge configuration (such as the example shown in Figure 1 of the accompanying drawings) are required.

Further reductions in switches can be made at the expense of motor efficiency by allowing phase current to flow only in a single direction. In this way continuous torque can be achieved from a 3 phase motor with only 3 switches. However this configuration has the problem that energy stored in the winding inductance has to be dissipated by a voltage clamp which may be part of the switch structure.

In order to establish a determined torque from the motor each switch has to connect its associated phase across a voltage source during the correct angles of rotation. This is known as commutation and the switching points are generally taken from measurements from one or more angular position sensors. It is then the generally accepted practice to regulate the motor speed or current by turning the current on and off during the commutation period at a frequency above the audible range, e.g. between 15kHz and 20kHz, and to vary the ratio of "on" time to "off" time to adjust the regulation. This technique of pulse width modulation (PWM) control is popular because it is an efficient and cost-effective method of achieving regulation. Its efficiency is achieved by storing the inductive energy during the time that the

switch is off, although with the three-phase configuration this cannot be achieved as the inductive energy is dissipated in the switch clamp (in turn causing a high switching loss).

With a specially designed four-phase motor, however, use can be made of the mutual coupling between the windings of opposite phases, as described for example in GB-A-2 297 433, to store efficiently the energy when the circuit is off.

A typical circuit of the switch and windings of a four-phase motor is shown schematically in Figure 2 of the accompanying drawings, and uses the reverse diode across each switch to conduct the current that flows due to the stored energy. This diode is usually integral with the switch structure and allows the stored energy to be transferred from the conducting phase to the opposing one and returned back into the supply.

This winding configuration also has a particular advantage in that it offers a practical optimisation of silicon (i.e. the semiconductor switches) and copper (i.e. the motor windings), utilising the copper and silicon for up to half the time compared to 2/3 and 1/6 of the time respectively in the case of the three phase bipolar motor. It also allows full PWM (pulse width modulation) control of the current using the mutual inductance of opposing phase pairs to usefully remove the stored energy in the winding inductance.

In Figure 2, the windings for the 4 phases are shown as W1 to W4 with polarity denoted by the dot convention. The corresponding phase switches are shown as S1 to S4 and their corresponding diodes shown as D1 to D4. The switches are controlled from commutation electronics which decode a position signal to provide the correct sequence for closing the switches. Typically this position signal would be provided by two Hall effect devices sensing the rotating magnetic field of the motor. The commutation will provide four decoded states to turn the switches on for either 90 degrees or 180 degrees as shown in Table 1 below.

The commutation truth table shown in Table 1 is essentially a fixed logical pattern. The switch-on and switch-off points for a particular motor are set by the mechanical positions of the Hall effect sensors HEF1 and HEF2. In order to achieve the required performance from a particular motor, the positions of these sensors must be mechanically adjusted or tuned.

The performance and control requirements of this type of motor can be understood with regard to the electrical model of each phase as shown in Figure 3 of the accompanying drawings. It is assumed that the motor has a magnetic field which moves in a rotary manner, although the principles apply equally well to a magnetic field which moves in a linear manner. Each phase is represented by a voltage source, an inductance and a resistance. The voltage source is known as the back EMF (electro-motive force) of the motor and is generated by the moving permanent magnetic field of the motor coupling to the winding. It provides a waveform that is cyclic with time and of a frequency equal to the rotational frequency of the motor multiplied by half the number of magnetic poles on the rotor. The profile of this cyclic wave form is dependent on the magnetic geometry of the motor and its magnitude its proportional to speed. The inductance and resistance represent the basic elements of the coil that makes up the winding.

Figure 4 of the accompanying drawings shows typical waveforms when the winding is energised to achieve torque from the motor. In this case the winding is energised when the back EMF is negative with respect to the supply voltage. When the switch is closed the current will then build up exponentially in the winding on a time constant set by the ratio of inductance to resistance and to a final value which if the difference between the supply voltage and the back EMF, or forcing voltage, divided by the resistance. The power produced by the motor is then the average product of current and back EMF, and the torque is given by the power divided by the rotational speed in radians/second.

For a motor with a substantially constant back EMF over the period of energisation then the torque is proportional to the mean current. At low speeds the winding can be energised for a time well in excess of the time constant and the current builds up to its steady state value, hence the mean current approaches the peak current. As the motor speed increases then the difference between supply voltage and the back EMF reduces as does the time available to establish the current. Hence not only is the steady state level of current less but also there is no time to reach it so that the mean level of current approaches half the peak level giving rise to a low mean torque.

In order to maintain a desired torque with increasing speed the forcing voltage has to be increased to maintain the same mean current which means that the back

EMF must be a smaller percentage of the supply voltage and thus that the motor must be run at a lower speed. The motor cannot produce its maximum power and is less efficient. It is conventional to reduce this limitation by turning the switch on and off earlier giving rise to a technique known as phase advance. However the power output is generally limited to a constant value when phase advance is applied.

This invention provides a brushless direct current motor comprising:

one or more position sensors for sensing the angular position of the motor;

means for generating an angular position signal from the output of the position sensor(s);

a plurality of switches for controlling current flow in respective phase windings of the motor;

means, responsive to the angular position signal, for generating control signals to control the phase switches to switch on and switch off current in the respective phase windings at respective angular positions of the motor.

The commutation electronics are now potentially more complicated than the simple combinational schemes described in Table 1, as a measurement of the phase or electrical angle of the motor is used. This may be made simply with a continuous measurement transducer, but for low cost applications it is preferred that the measurement is made using a limited number of discrete position indicators, such as Hall effect switches. These sensors indicate individual "events" (e.g. the time when a magnetic pole of the motor passes one of the sensors), and so the motor position between the events can be calculated or interpolated. Times can then be derived at which each phase should be turned on and off; however, in contrast to the fixed commutation logic described with reference to Figure 1, these switching times need not be dependent on the accuracy of positioning of the Hall effect sensors, and they need not be fixed across a range of motor speeds. In fact, in a preferred embodiment, the switching times are substantially independent of the discrete event sensors - the sensors are used simply to initiate the generation of a cyclic (e.g. ramped) angular position signal. Preferably the angular switching times are variable, for example being dependent on motor speed.

The invention can be used in various embodiments to improve the phase advance technique described earlier, by (for example) delaying the turn off time of a

phase switch to give extended commutation (i.e. increasing the angle over which the current is turned on). As a result, the motor can then be capable of producing greater power and efficiency.

The measurement of angle in the preferred embodiments described above is dynamic in that the motor has to be rotating for a measurement to be made, so there may be a minimum speed below which the accuracy of the position measurement cannot be maintained. Preferably, this is detected and suitable action taken such as forcing the motor commutation into a combinational logic decoding state such as that in Table 1. The motor can return to the variable decoding and switching arrangement when the motor speed reaches a predetermined value.

One embodiment of the invention uses an analogue method to develop the angle measurement and a digital method of implementing the commutation.

In embodiments of the invention, the facility to vary the switching times of the windings can be used to alleviate the limitations described above by (for example) moving the conduction period to earlier in the back EMF cycle so that the voltage across the inductor is initially greater, and then reduces as the current builds up. This allows the current to build up rapidly to start with and then more slowly as the region of constant back EMF is reached, thus the mean current will be closer to the peak and more power may be achieved from the motor.

A further and substantial increase in power and efficiency can also be obtained using embodiments of the arrangement defined above by delaying the turn off of the switch until the peak back EMF has passed. In practice the conditions for maximum (or at least improved) efficiency are found when the conduction advance is sufficient to maintain a constant current during the period of constant back EMF. It is thus preferable to control both the angle at which the phase winding should be turned on and the angle for which it is on. Optimum or at least preferred values for these parameters will vary with different motor sizes, voltages, speeds and torque outputs, but may be predetermined for a given application. The conduction advance and on angle may then be controlled by a look up table.

An additional advantage with this method of conduction control is that the effective motor torque constant can be varied to produce an enhanced speed at low torques and a reduced supply current at high torques. This can be applied with a

PWM control strategy so that at conditions where maximum power or speed is not required from the motor (i.e. PWM is less than 100%) then conduction advance and conduction angle is reduced. For conditions where maximum power is required from the motor (i.e. PWM is close to or equal to 100%) then the conduction advance and conduction angle can be increased to give maximum power or speed.

In one embodiment, a conventional phase locked loop (PLL) can be used to control a voltage controlled oscillator to derive a motor angle measurement. However, this would suffer from a relatively poor dynamic response. In another preferred embodiment, the angle measurement is preferably based on a new technique to be referred to as a period based phase correction loop (PBPCL).

Using a conventional PLL system, a voltage controlled oscillator (VCO) is brought into phase with the input frequency by varying the frequency of the oscillator. If the oscillator is embodied as a resettable ramp waveform, then when the oscillator is in phase with the input the PLL can be considered to be IN LOCK and the ramp voltage can be considered to be a measurement of angle. This can then be used to control the turn on angle and turn off angle of the phase switches. When the oscillator is not IN LOCK then it is preferred that the control of the switches can default to the direct combinational decoding of the Hall effect signals shown in Table 1.

However, although the invention will operate with PLL system, under transient conditions the phase shift between the oscillator frequency and the input frequency can exceed 180 degrees before the loss of lock is detected, thus causing the winding to be energised in the wrong part of the cycle leading to the generation of negative rather than positive torque.

This problem is addressed in the PBPCL system, as the ramp control voltage produces a ramp proportional to angle (or phase). which is reset at each input. However before resetting the ramp voltage is compared to a fixed level representing a predetermined angular position such as 90 degrees, and the ramp control voltage increased or decreased according to whether the ramp is less than or greater than the fixed level. In this way although the measurement of angle may be in error it can be detected at each input transition and is not cumulative as in the conventional PLL. Using a simple window circuit, the IN LOCK signal may be corrected every cycle and the appropriate commutation strategy executed without the problems seen in a

conventional PLL system.

Accordingly, the invention also provides an integrator for generating a cyclic voltage ramp signal in synchronism with one or more periodic discrete event signals, the integrator comprising means for periodically resetting the voltage ramp signal and comparing an instantaneous level of the ramp signal to a predetermined calibration signal.

This invention also provides a brushless direct current motor controller for controlling a motor having one or more position sensors for sensing the angular position of the motor; the controller comprising:

means for generating an angular position signal from the output of the position sensor(s);

a plurality of switches for controlling current flow in respective phase windings of the motor;

means, responsive to the angular position signal, for generating control signals to control the phase switches to switch on and switch off current in the respective phase windings at respective angular positions of the motor.

The invention will now be described by way of example with reference to the accompanying drawings, throughout which like parts are referred to by like references, and in which:

Figure 1 is a schematic diagram of a previously proposed three-phase brushless dc motor and control electronics;

Figure 2 is a schematic diagram of a previously proposed four-phase brushless dc motor and control electronics;

Figure 3 is a schematic electrical model of each phase of the motor of Figure 2;

Figure 4 is a schematic timing diagram illustrating control waveforms for one phase of the motor of Figure 2;

Figure 5 is a schematic timing diagram illustrating control waveforms for a motor according to an embodiment of the invention;

Figure 6 is a schematic block diagram of a commutation control circuit;

Figure 7 is a schematic circuit diagram of a period based phase correction loop (PBPCL);

Figure 8 is a schematic circuit diagram of a phase advance duration control circuit;

Figure 9 is a schematic circuit diagram of a commutation logic circuit; and

Figure 10 is a schematic timing diagram illustrating signal waveforms of the circuit of Figure 9.

In the embodiment to be described below, so-called event or position sensors (such as Hall effect sensors) are used to sense discrete rotational positions in the motor's travel. A substantially continuous ramped electrical signal representing the motor's angular position is then generated by synchronising to the outputs of the event sensors. The switch-on and switch-off times for the windings can be advanced or retarded simply by setting a different level of the angular position signal (otherwise referred to as the angle ramp voltage) to trigger the switch-on or switch-off. At low or zero motor speeds, the synchronisation to the discrete event sensors tends to be inaccurate, so the commutation logic reverts to a simple combinational arrangement (such as that shown in Table 1) to get the motor going. However, during normal operating conditions, it is expected that the more advanced timing arrangement using the angular position signal would be used.

The potential benefits of a variable advance/retardation of the switching times will first be discussed with reference to Figure 5, which illustrates timing waveforms for the back EMF, the switching times and the resulting winding current for a simple 90 degree phase advance and an extended phase advance arrangement.

As described above, for moderate to high speed conditions, the current build up in the winding is limited by the inductance of the winding and because the rate of build up of current under these conditions is limited by the voltage across the inductor then by turning the winding on around the region of peak back EMF (also the peak torque constant) the motor has to be slower than it needs to establish a given mean current. However, in the present embodiment, the facility to vary the switching times of the windings can be used to alleviate this limitation described above by moving the conduction period to earlier in the back EMF cycle so that the voltage across the inductor is initially greater, and then reduces as the current builds up. This allows the current to build up rapidly to start with and then more slowly as the region of constant back EMF is reached, thus the mean current will be closer to the peak and more power

may be achieved from the motor.

Accordingly, Figure 5 illustrates a phase advance of 90 degrees and the resulting current flow through the winding against the back EMF, and a phase advance of 90 degrees with a total switched-on angle of more than 90 degrees and less than 180 degrees.

Figure 6 is a schematic diagram of a commutation control circuit.

In Figure 6, the output of a number of discrete Hall effect sensors 100 is supplied to a PBPCL circuit 102 which locks to the sensed events and generates a ramped angular position signal 104 and an "IN LOCK" signal 106 indicating whether the PBPCL circuit has achieved lock with the output of the Hall effect sensors. The PBPCL circuit will be described in more detail below with reference to Figure 7.

The angular position signal is supplied to a phase advance duration control circuit 108, which will be described in more detail below with reference to Figure 8. The phase advance duration control circuit generates two output signals, namely a "COM START" signal 110 indicating a switch-on time for each phase, and a "COM END" signal 112 indicating a switch-off time for each phase.

The Hall effect sensor outputs, the IN LOCK signal 106, the COM START signal 110 and the COM END signal 112 are all supplied to a commutation logic circuit 114. This circuit, which will be described in more detail below with reference to Figure 9, generates **either** phase switching control signals DO1 to DO4 for normal operation, based on the timings specified by the COM START and COM END signals, **or** phase switching control signals DS1 to DS4 for low speed operation when the PBPCL circuit is not locked, based only on the Hall effect sensor outputs.

The phase advance duration control circuit 108 and the commutation logic 114 are also controllable by a PWM control signal, to vary the duty cycle of a PW-modulated output of the circuit.

Figure 7 schematically shows the circuit elements in a PBPCL. IC1 forms an integrator that holds the dc ramp control voltage. This voltage is inverted in IC2 and is used to drive the resettable integrator formed by IC4. IC4 generates the ramp voltage proportional to angle and is reset at each Hall effect edge transition by closing S3 for approximately 10μS (microseconds) using a logic pulse generated in IC9, IC10 and IC11. IC9 takes the exclusive OR of the two Hall effect sensor inputs and

provides an output in which each alternate Hall effect edge produces a positive going transition and each intermediate one produces a negative going transition. Each edge is then translated into a positive fixed width pulse at the output of IC11 by using the Q output of IC10 to provide a polarity control input to IC11. When a Hall effect edge changes it changes the corresponding input to IC11 which in turn forces the output of IC11 sign. The voltage across C: which was zero, rises toward the output voltage on IC11 and when it reaches the clock threshold on IC10 the D input is transferred to the Q. Both inputs to IC11 now take on the same value forcing the output of IC11 low and causing C4 to discharge to zero. By arranging the time constant of R17, C4 to be about 10μS than a positive pulse of this duration will appear at the output of IC11. This pulse is denoted CLKA and is used to latch the ramp error, the lock window and generate a delayed pulse through R18, C5 and IC12.

The resistor chain R13 to R16 sets the mean and limit values for the angle ramp. The mean voltage appearing at the midpoint between R14 and R15 is buffered in IC5 and is used as the reference voltage for C3. This voltage is equivalent to an angle of 90 degrees. During the ramp S4 is set to A under control of the TRANSFER signal which is low. At the end of the ramp, when the Hall effect edge changes, the rising edge of CLKA latches the output of IC6 into IC15, it records whether the ramp voltage was either below or above the mean value and provides the POLARITY signal. After about 2μS as set by the time constant of R18 and C5 the ramp voltage is then reset to zero by CLKC which is a low level pulse of approximately 10μS in duration. The time constant of R18 and C5 also delays by about 2μS the time at which IC14 is clocked relative to IC15 ensuring that the output of IC16 is low and the high level on the D input is latched at the Q output. Thus the TRANSFER signal is set high closing S2 and setting S4 to position B. The POLARITY signal sets S5 to position B which causes the voltage across C3 to reduce to zero. At this point the output of IC6 changes state setting the output of IC16 high, resetting IC14 forcing the TRANSFER signal low. This returns S4 to position A and allows C3 to measure the next ramp voltage.

During the period that the TRANSFER signal is held high the ramp control voltage is adjusted to make the end of the ramp voltage at the next Hall effect transition equal the 90 degrees voltage. For instance if the angle ramp voltage was

below the reference voltage at the transition then the POLARITY signal will be high and the ramp control voltage needs to be increased. This is achieved by using the POLARITY signal to set S1 to position A for the time that the TRANSFER signal is high. This is determined by the time taken to discharge the voltage across C3 to zero. As the voltage on plate A of C3 will be less than the 90 degrees voltage then the POLARITY signal will set S6 to position B, allowing the voltage on plate A of C3 to increase. Conversely switches S1 and S5 will be set to position B by a low level POLARITY signal if the end of ramp voltage is greater than the 90 degrees voltage. At this end of ramp voltage approaches the 90 degrees voltage then the time for which the TRANSFER signal is held high reduces and the adjustment in ramp control voltage approaches zero. The ratio of (R9 in parallel with R10).C3 to R1.C1 and (R11 in parallel with R12).C3 to R2.C1 is critical to the response time of the feedback circuit and with values as shown the circuit will come into lock within 7 Hall effect edges after a step change in edge frequency. By suitable reduction of these values the circuit can exhibit a classical "dead beat" response and will come into lock within 1 Hall effect edge after a step change in edge frequency.

In order to increase the range of Hall effect transition frequencies over which the circuit will work it is arranged that the magnitude of the ramp adjustment voltage will be proportional to itself and will thus compensate for the variations in time between Hall effect transitions over a wide range of motor speeds. This is successful except for conditions when the voltage on IC1 needs to be increased from very low levels, in the order of millivolts. Under these conditions it is possible that the adjustment voltage at the output of IC2 can appear positive due to the influence of amplifier offset currents and voltages. The voltage on IC1 would then increase in a negative direction aided by the control loop and the angle ramp would go negative. In order to prevent this IC3, D1, R6, R7, and R8 are used to actively clamp the output from IC2 preventing it going positive.

The positive and negative voltage limits for the ramp are set across R14 and R16 respectively. These levels are compared with the angle ramp voltage in the window comparator is latched at the end of each ramp in IC13 by the rising edge of CLKA. If the output is high then the angle ramp voltage is within acceptable limits and the VCO is IN LOCK.

Figure 8 shows the circuit to generate the signals to turn the phase switches on and off.

To turn a phase switch on the angle ramp is compared in IC100 to the PHASE START VOLTAGE derived in the voltage divider circuit formed by R100 and R101. (This could be made variable by providing a variable resistor for one or both of R100 and R101, or it could be varied in dependence on, for example, the motor speed by adding or subtracting a difference voltage to the output of the voltage divider). When the angle ramp voltage exceeds the PHASE START VOLTAGE then the output of IC100 is pulled high by R102 producing a positive going pulse of approximately 10μS in duration across R100 via C100. This pulse sets the bistable circuit formed by IC101 and IC102. The high going output of IC102 generates a low active pulse known as COM START of duration approximately equal to 10μS using the circuit formed by R109, C103, IC107 and IC108. If the PBPCL circuit is IN LOCK then this pulse is gated with the decoded Hall effect states to set a bistable circuit corresponding with the correct phase switch turning the switch on.

To turn a phase switch off the high level set on IC102 opens the reset switch S100. The output of IC103 now starts to rise from its reset value of zero at a rate controlled by R104, C101, and the inverted RAMP CONTROL VOLTAGE. The values for R104 and C101 match those for R5 and C2 respectively causing the rate of change in output voltage from IC103 to be the same as the ANGLE RAMP VOLTAGE. Thus the output voltage of IC103 is proportional to the motor angle and is defined as the ON RAMP VOLTAGE. This voltage is compared in IC104 to the PHASE OFF VOLTAGE derived in the voltage divider circuit formed by R105 and R106. The output of IC104 is pulled high by R107 when the ON RAMP VOLTAGE is greater than or equal to the PHASE OFF VOLTAGE resetting the bistable formed by IC101 and IC102. When the output of IC101 goes high then the reset switch S100 closes, discharging S100 forging the output of IC108 to get zero. A pulse of duration approximately equal to 10μS and known as COM END is also generated from the rising edge of IC101 using the circuit formed by R108, C102, IC105 and IC106. If the PBPCL circuit is IN LOCK then this pulse is gated with the decoded Hall effect states to reset a bistable circuit corresponding with the correct phase switch turning the switch off.

Figure 9 shows the commutation logic circuit that uses these pulses to turn each phase on and off. Figure 10 shows the corresponding waveforms.

The commutation logic is composed of two sections: the first is a combinational logic section formed by IC109 to IC114, and the second is composed of four gated memory sections each of which is formed by logic elements such as is shown by IC115 to IC128 for phase1 switch control.

The combinational logic section generates the phase switching control signals for use when the PBPCL is not in lock (usually at low motor speeds), and decodes the four logic states DS1 to DS4 formed by the two Hall effect inputs HEF1 and HEF2 according to the 90 degrees truth table shown in Table 1. These logic states are then translated in each of the memory sections to provide the switch drive signals.

The memory sections provide the control signals for use when the PBPCL is in lock. They comprise set-reset bistable formed from IC126 and IC127. The set input is controlled from one of the decoded outputs from the combinational logic section as determined the state of the IN LOCK signal. If the PBPCL is not in lock then the IN LOCK signal is low and the NOT IN LOCK signal provided by IC118 is high hence the output of IC115 is held low inhibiting IC119. The output of IC117 is also held low inhibiting IC121. This only leaves IC120 active, allowing the basic decoded state to set the bistable. The output of the bistable is inverted in IC128 to provide a positive logic drive signal and a feedback signal which is used in the reset logic of the other three memory sub sets. For the phase 1 as shown IC123 is inhibited whilst IC122 is enabled. Thus phase 1 will be turned off when the bistable is reset by any of the other phase switches DO2, DO3 or DO4 are turned on.

Using the outputs that control the phase switches in this way to reset the bistables rather than using the decoded outputs of the Hall effect states directly is necessary when the PBPCL circuit is IN LOCK and control of the switch angles is enabled. In this state the turn off angle can span more than one decoded Hall effect state particularly for highly advanced turn on angles or small angles of energisation. When the IN LOCK signal is high IC119 is inhibited leaving IC120 and IC121 which are enabled to set the bistable. IC120 gates the COM START pulse with the previous decoded Hall effect state, thus for phase 1 this will be the decoded state for phase 4 whilst IC121 gates the default decoded state with the CLKC pulse to ensure that the

phase switch is turned on in the absence of a COM START pulse. The bistable is reset via IC123 and the complimentary output states. IC123 gates the COM END pulse with the phase switch to be energised next in sequence, this means that for phase 1 the next phase to be set is phase 2. The complimentary output state ensures that opposite phases cannot be on together causing a short circuit across the supply.

The four outputs derived in this way can then be gated by a PWM gate 201 (under control of the PWM control signal described above) to Enable or provide Pulse Width Modulation control of the switches.

Figure 10 is a schematic timing diagram which illustrates the following signals:

- the outputs of the Hall effect sensors HEF1 and HEF2;
- the "non-locked" combinational control signals DS1 to DS4;
- the angular position signal 104 and the PHASE START VOLTAGE;
- the COM START and COM END signals 110, 112;
- the output of IC103; and
- the "in lock" control signals DO1 to DO4.

It will be seen that each of the control signals DO1 to DO4 has a rising edge aligned with a respective COM START pulse, and a falling edge aligned with a respective COM END pulse. Furthermore, each "COM START" pulse is aligned with the crossing of the angular position signal 104 and the PHASE START VOLTAGE.

In summary, therefore, embodiments of the invention provide a brushless dc motor controller comprising of electronic switches to control the current flow in each phase of the motor. Event sensors are used to detect certain positions of the magnet flux of the motor. These switches are turned on or off by outputs from a commutation circuit which decodes the outputs from the event sensors. Operation of these switches is extended over a greater angular range by turning the switches on earlier and holding them on for longer in order to achieve a greater power output and efficiency from the motor. A Phase Resetting VCO is used to predict the angle between sensor events and this is compared to a start angle and an on angle which will be set for maximum power output. These comparisons are then used in a gated bistable circuit to generate the switch control signals.

Table 1

	HEF2	HEF1	S1	S2	S3	S4
90° Conduction	0	0	on	off	off	off
	0	1	off	on	off	off
	1	1	off	off	on	off
	1	0	off	off	off	on
180° Conduction	0	0	on	on	off	off
	0	1	off	on	on	off
	1	1	off	off	on	on
	1	0	on	off	off	on

CLAIMS

1. A brushless direct current motor comprising:

one or more position sensors for sensing the angular position of the motor;

means for generating an angular position signal from the output of the position sensor(s);

a plurality of switches for controlling current flow in respective phase windings of the motor;

means, responsive to the angular position signal, for generating control signals to control the switches to switch on and switch off current in the respective phase windings at respective angular positions of the motor.

2. A motor according to claim 1, in which the energisation of the switches is variable with respect to the output of the position sensor(s).

3. A motor according to claim 1 or claim 2, in which the one or more position sensors are discrete position sensors operable to generate an output signal indicating that the angular position of the motor has reached a predetermined position.

4. A motor according to claim 3, in which the one or more position sensors are Hall effect sensors.

5. A motor according to claim 2 or claim 3, comprising means for generating a cyclic voltage ramp signal having a magnitude substantially linearly related to the motor's angular position with respect to the one or more position sensors.

6. A motor according to claim 5, comprising two position sensors, one sensor initiating generation of the voltage ramp signal from an initial voltage and the other sensor resetting the voltage ramp signal to the initial voltage.

7. A motor according to claim 5 or claim 6, in which the generating means comprises an integrator having a substantially constant slope rate, to generate the

voltage ramp signal substantially linearly related to motor rotation over a predetermined angular range.

8. A motor according to claim 4 or claim 5, comprising:

combinational control logic generating further control signals to control the switches in a predetermined sequence directly derived from the output of the position sensor(s);

means for detecting whether the motor speed is less than a predetermined lower limit;

means, responsive to a detection that the motor speed is less than the predetermined limit, for controlling the switches according to the further control signals generated by the combinational control logic;

means responsive to a detection that the motor speed is greater than the predetermined limit for extending the angular range of the control signals from the combinatorial logic using a gated bistable circuit.

9. A motor according to claim 8, comprising means for comparing the angular position signal with two switching signal levels, a comparison with one switching level controlling turning the switch on and a comparison with the other level controlling turning the switch off.

10. A motor according to claim 9, comprising means, responsive to the comparing means, for extending the angular range of the switches as set by the combinatorial logic using the gated bistable circuit.

11. A motor according to claim 8, in which the detecting means comprises means for detecting whether the ramp voltage is locked to the output of the position sensor(s).

12. A motor according to any one of the preceding claims, in which:

the current flow through each phase winding of the motor, when energised, is controllable by pulse width modulation using a pulse width modulation control signal;

and

the angular position and/or duration of current flow through each phase winding is controllable by the pulse width modulation signal.

13. A brushless direct current motor controller for controlling a motor having one or more position sensors for sensing the angular position of the motor; the controller comprising:

means for generating an angular position signal from the output of the position sensor(s);

a plurality of switches for controlling current flow in respective phase windings of the motor;

means, responsive to the angular position signal, for generating control signals to control the switches to switch on and switch off current in the respective phase windings at respective angular positions of the motor.

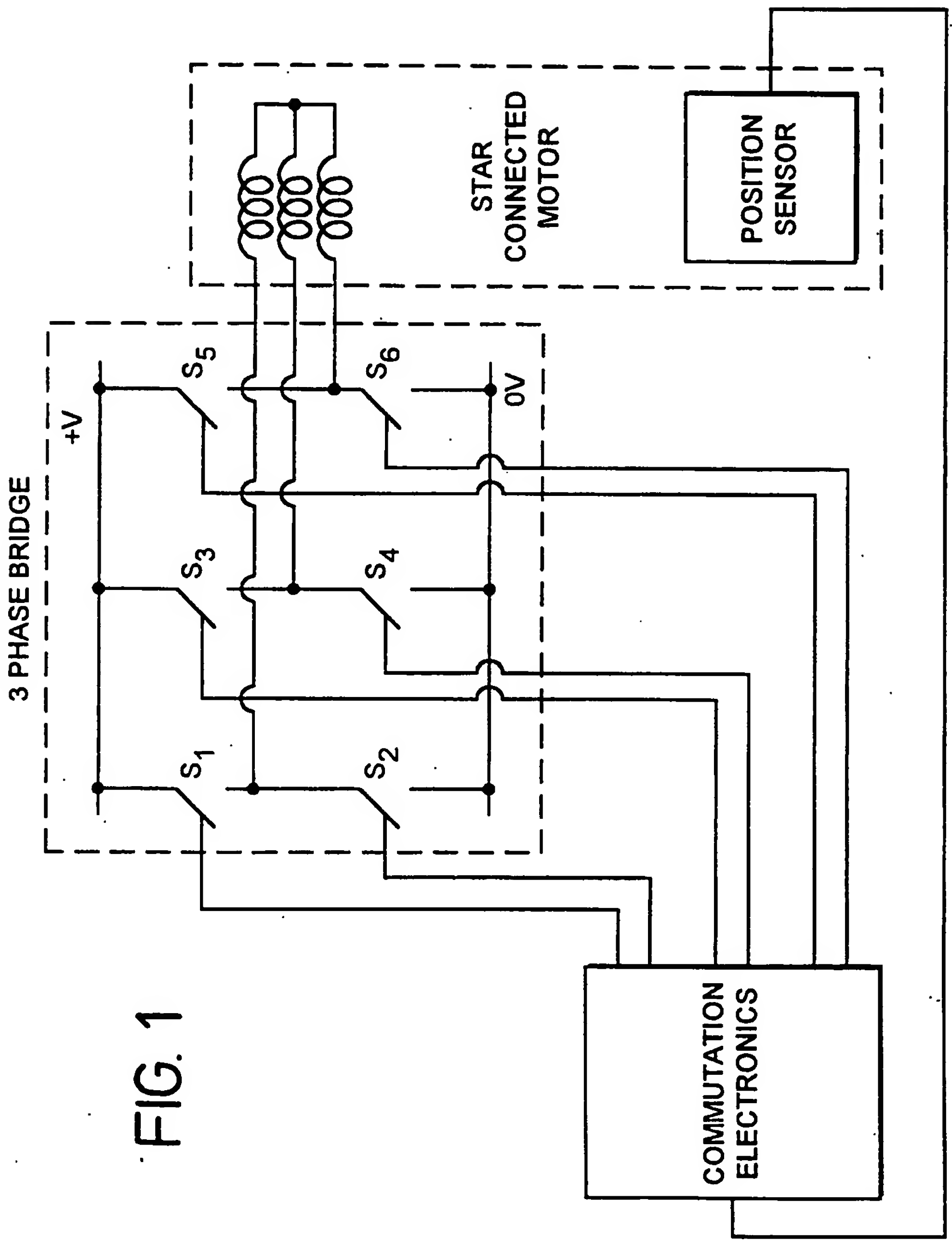
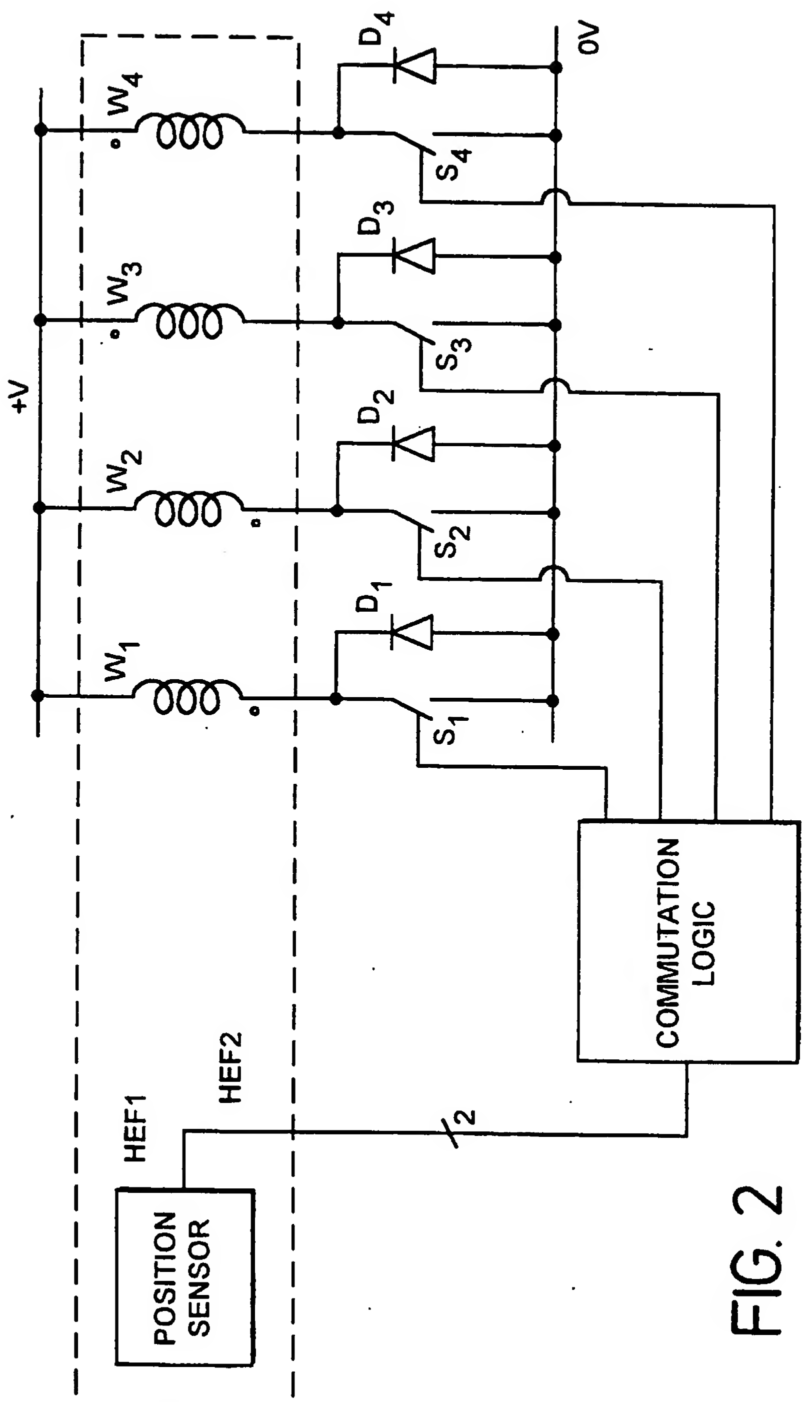

3 PHASE BRIDGE
+V
S_1
S_2
S_3
S_4
S_5
S_6
0V
STAR CONNECTED MOTOR
POSITION SENSOR
COMMUTATION ELECTRONICS

FIG. 1



0V
D_4
W_4
S_4
D_3
W_3
S_3
+V
D_2
W_2
S_2
D_1
W_1
S_1
COMMUTATION LOGIC
HEF1
HEF2
2
POSITION SENSOR

FIG. 2

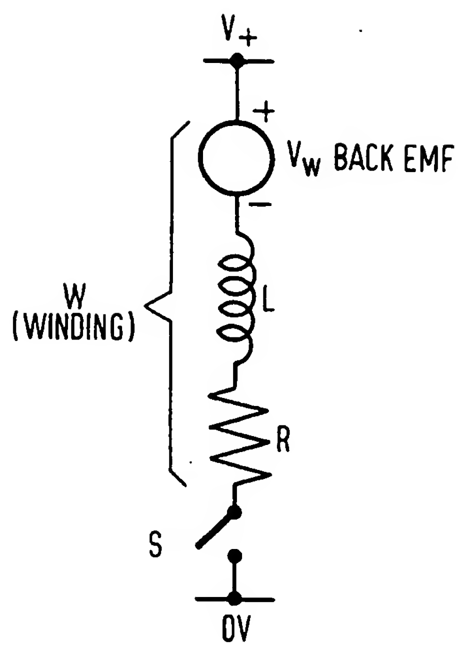


FIG. 3

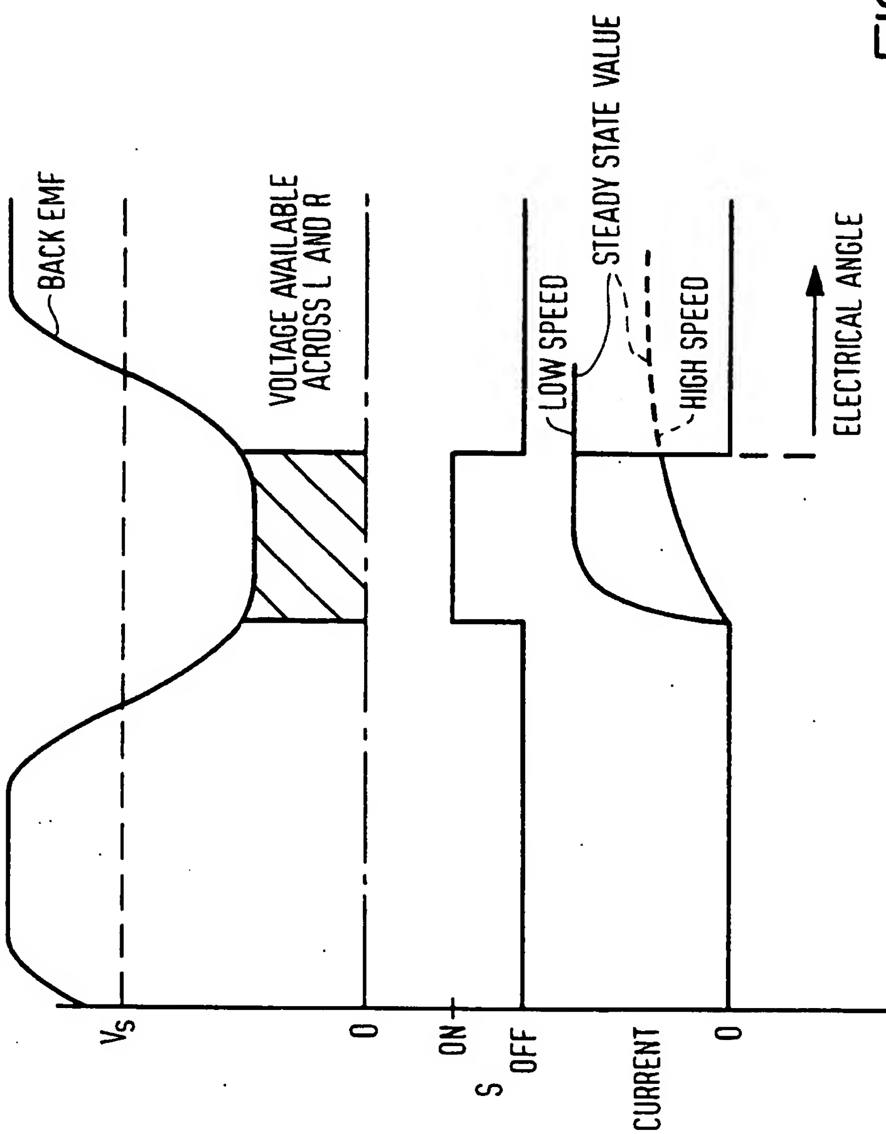
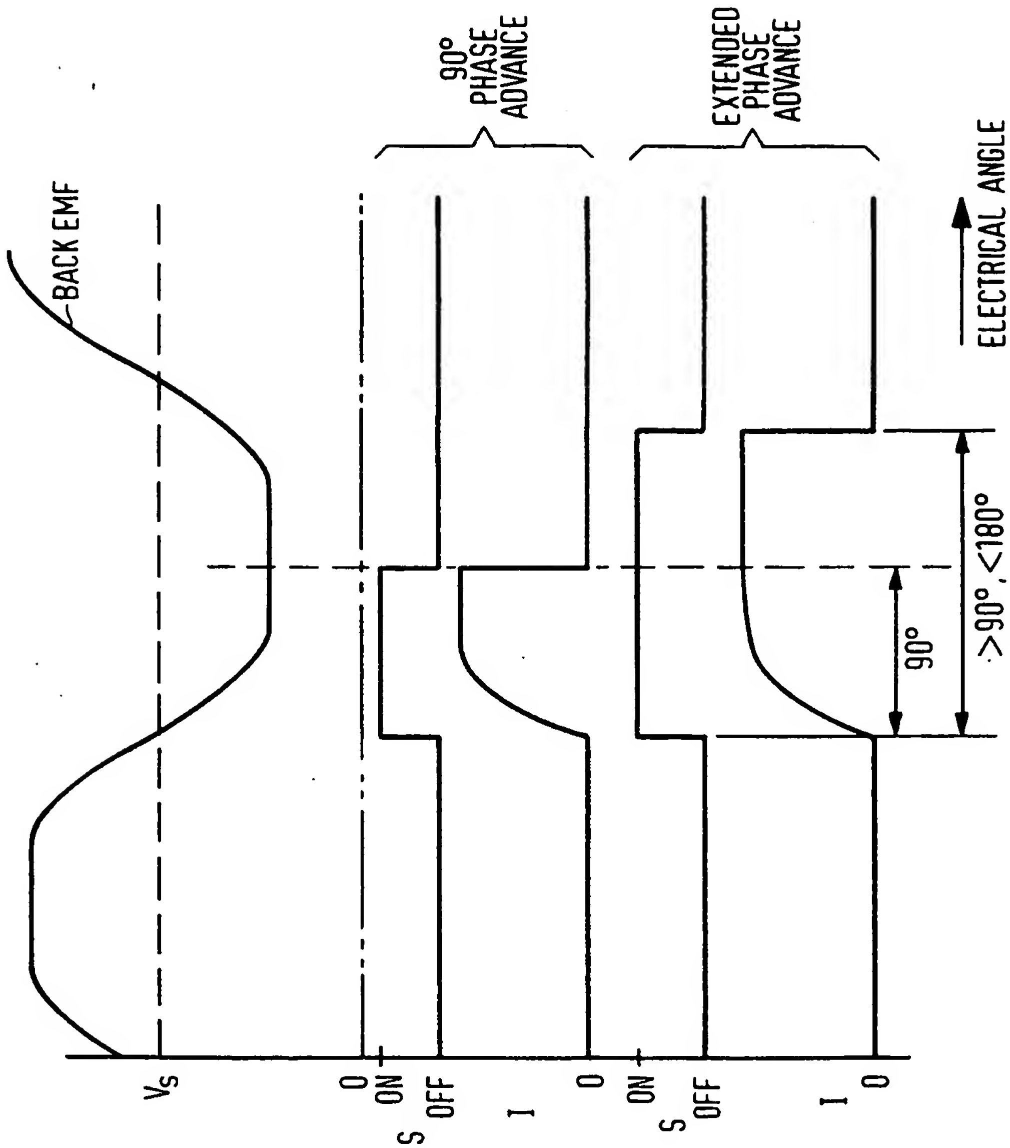

BACK EMF
VOLTAGE AVAILABLE ACROSS L AND R
LOW SPEED
STEADY STATE VALUE
HIGH SPEED
ELECTRICAL ANGLE
Vs
0
ON
S
OFF
CURRENT
0

FIG. 4

FIG. 5


BACK EMF
90°
PHASE
ADVANCE
EXTENDED
PHASE
ADVANCE
ELECTRICAL ANGLE
90°
>90°,<180°
V_S
0
ON
S
OFF
I
0
ON
S
OFF
I
0

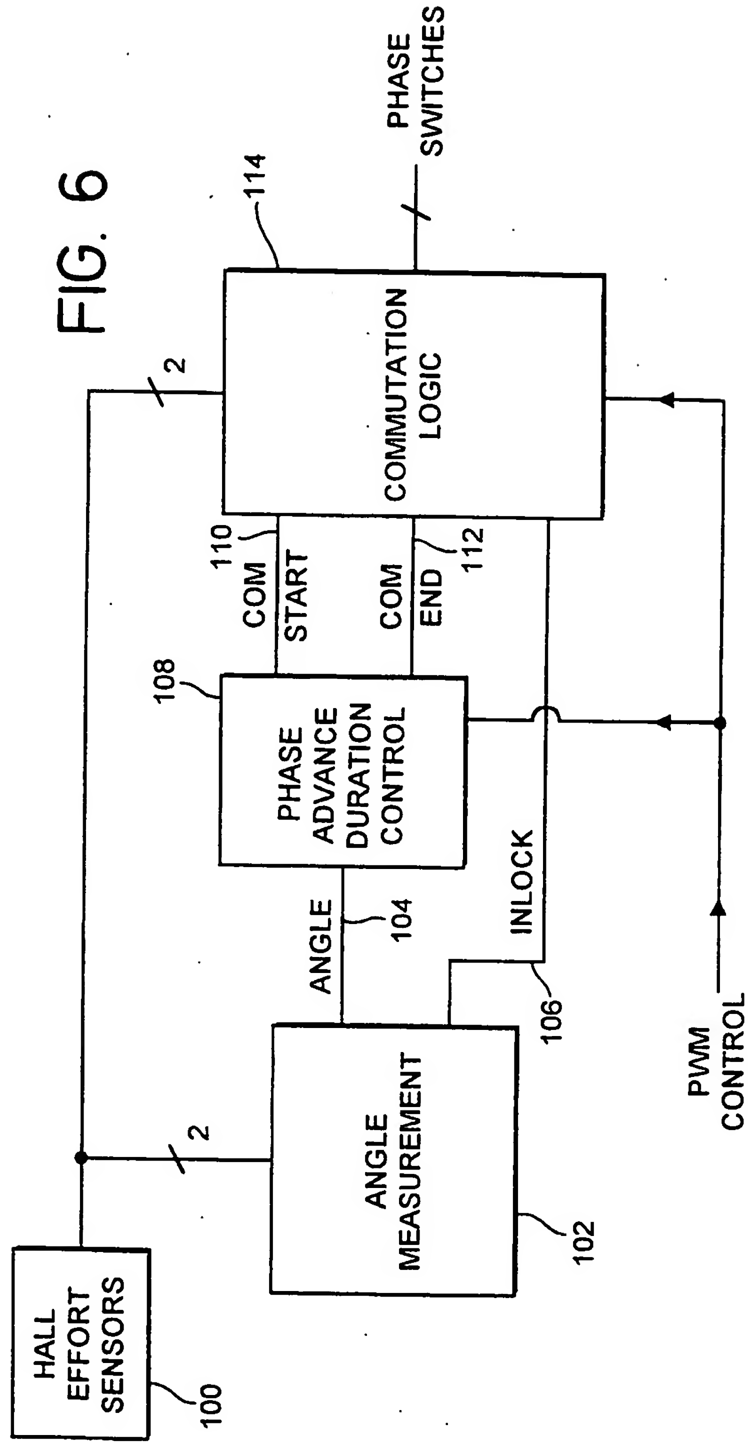

HALL
EFFORT
SENSORS
100
2
ANGLE
MEASUREMENT
102
ANGLE
104
INLOCK
106
PHASE
ADVANCE
DURATION
CONTROL
108
COM
START
110
COM
END
112
COMMUTATION
LOGIC
114
2
PHASE
SWITCHES
PWM
CONTROL

FIG. 6

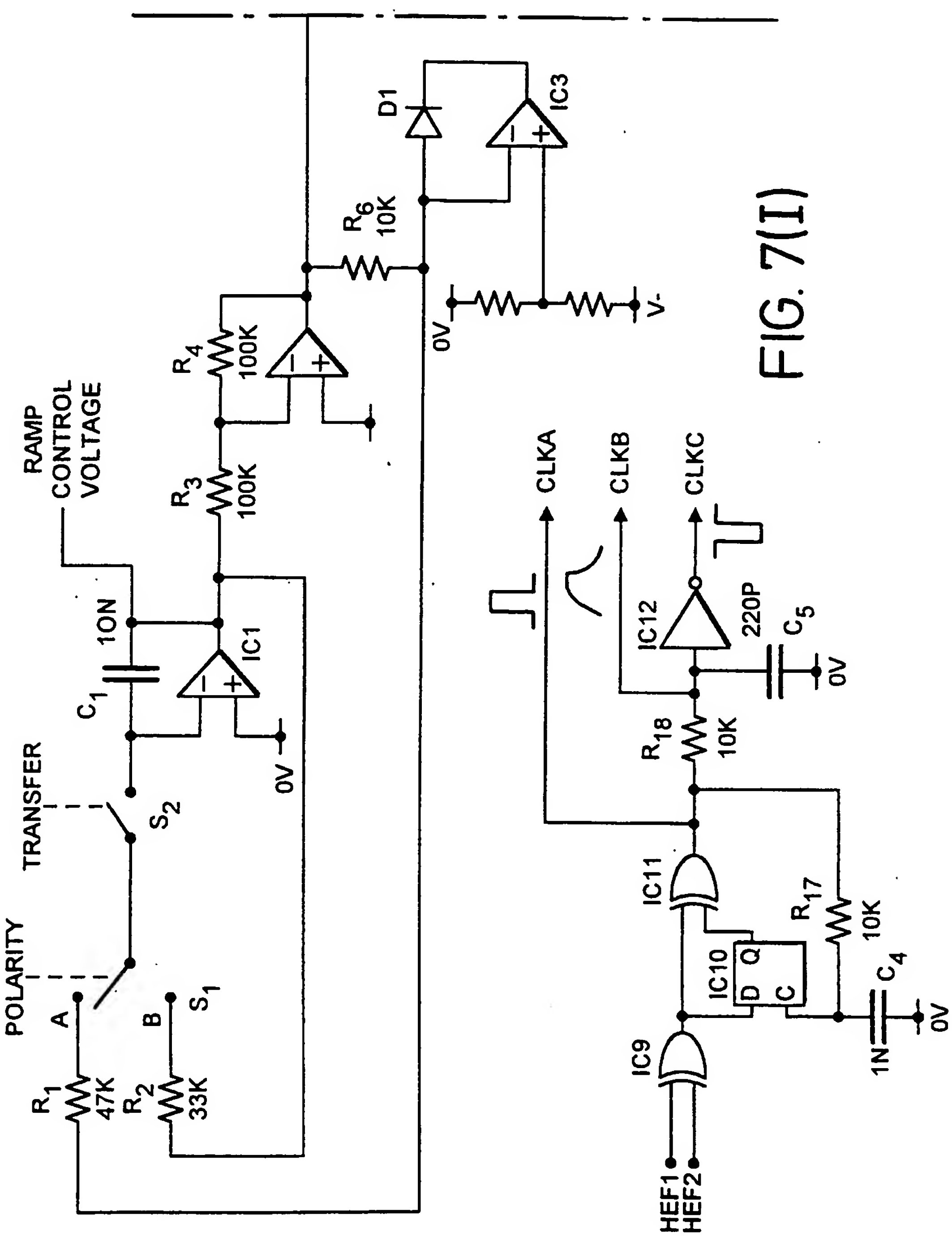

RAMP
CONTROL
VOLTAGE
TRANSFER
POLARITY
A
B
S_1
S_2
C_1
10N
IC1
0V
R_1
47K
R_2
33K
R_3
100K
R_4
100K
R_6
10K
D1
IC3
0V
V-
CLKA
CLKB
CLKC
IC12
220P
C_5
0V
R_{18}
10K
IC11
IC10
D
C
Q
R_{17}
10K
C_4
1N
0V
IC9
HEF1
HEF2

FIG. 7(I)

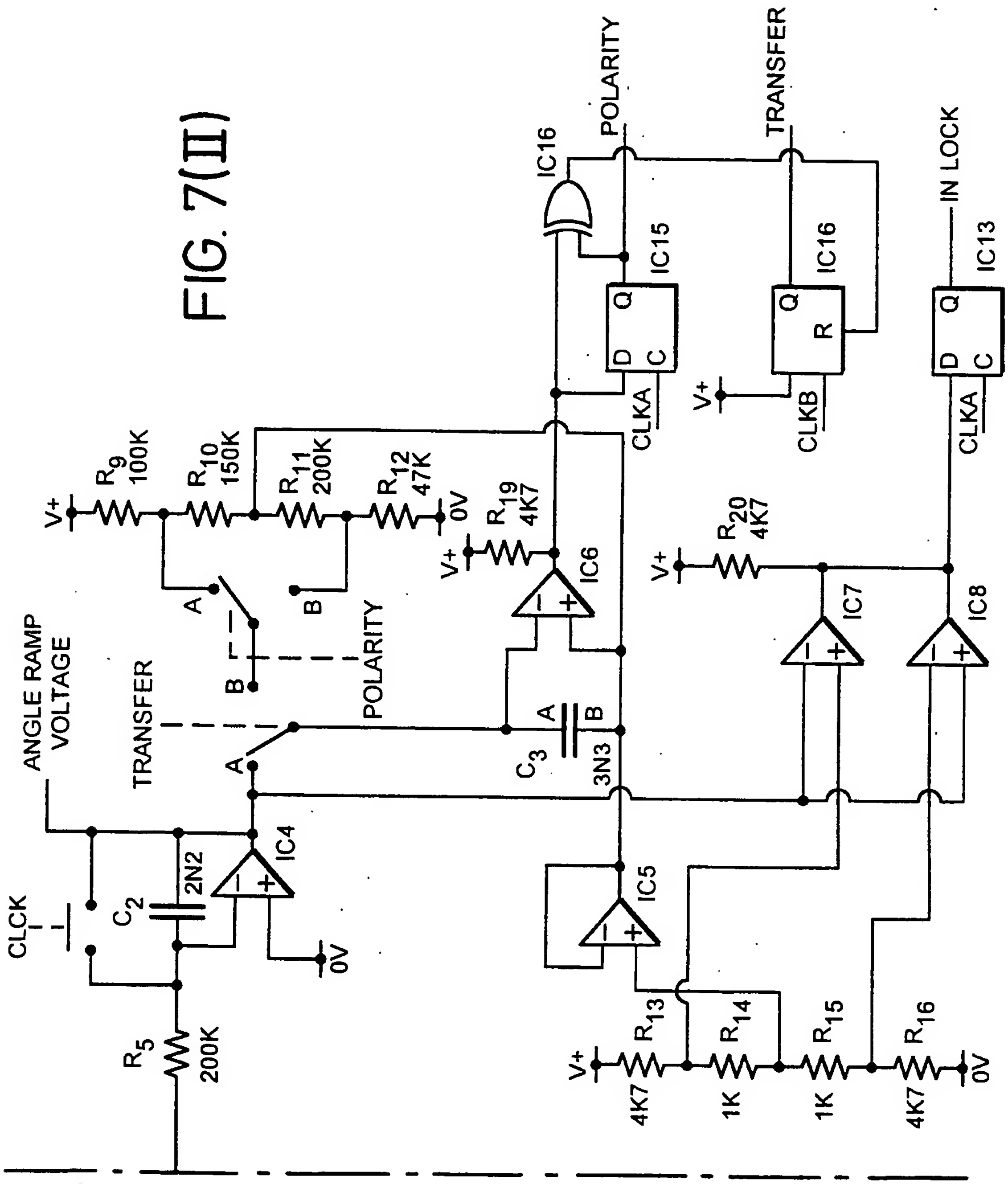

ANGLE RAMP VOLTAGE
CLCK
C_2
2N2
IC4
0V
R_5
200K
TRANSFER
A
B
POLARITY
V+
R_9 100K
R_{10} 150K
R_{11} 200K
R_{12} 47K
R_{19} 4K7
IC6
C_3
3N3
IC5
R_{13} 4K7
R_{14} 1K
R_{15} 1K
R_{16} 4K7
IC16
IC15
D
C
Q
R
CLKA
CLKB
R_{20} 4K7
IC7
IC8
IC13
IN LOCK

FIG. 7(II)

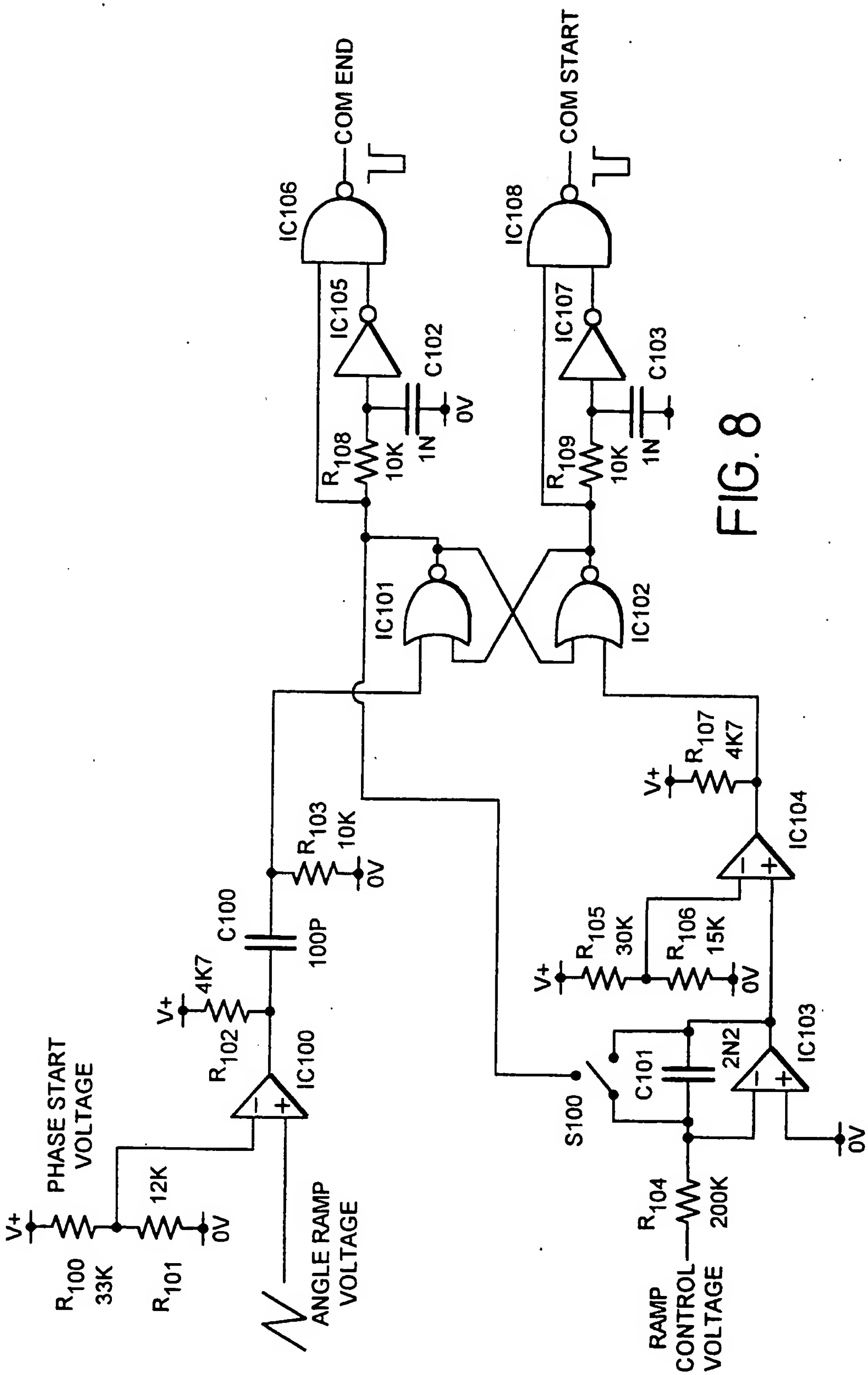

COM END
COM START
IC106
IC108
IC105
IC107
C102
C103
0V
1N
R108
10K
R109
IC101
IC102
R107
4K7
V+
IC104
R103
10K
C100
100P
R102
4K7
IC100
R105
30K
R106
15K
C101
2N2
IC103
S100
PHASE START VOLTAGE
R100
33K
R101
12K
ANGLE RAMP VOLTAGE
R104
200K
RAMP CONTROL VOLTAGE

FIG. 8

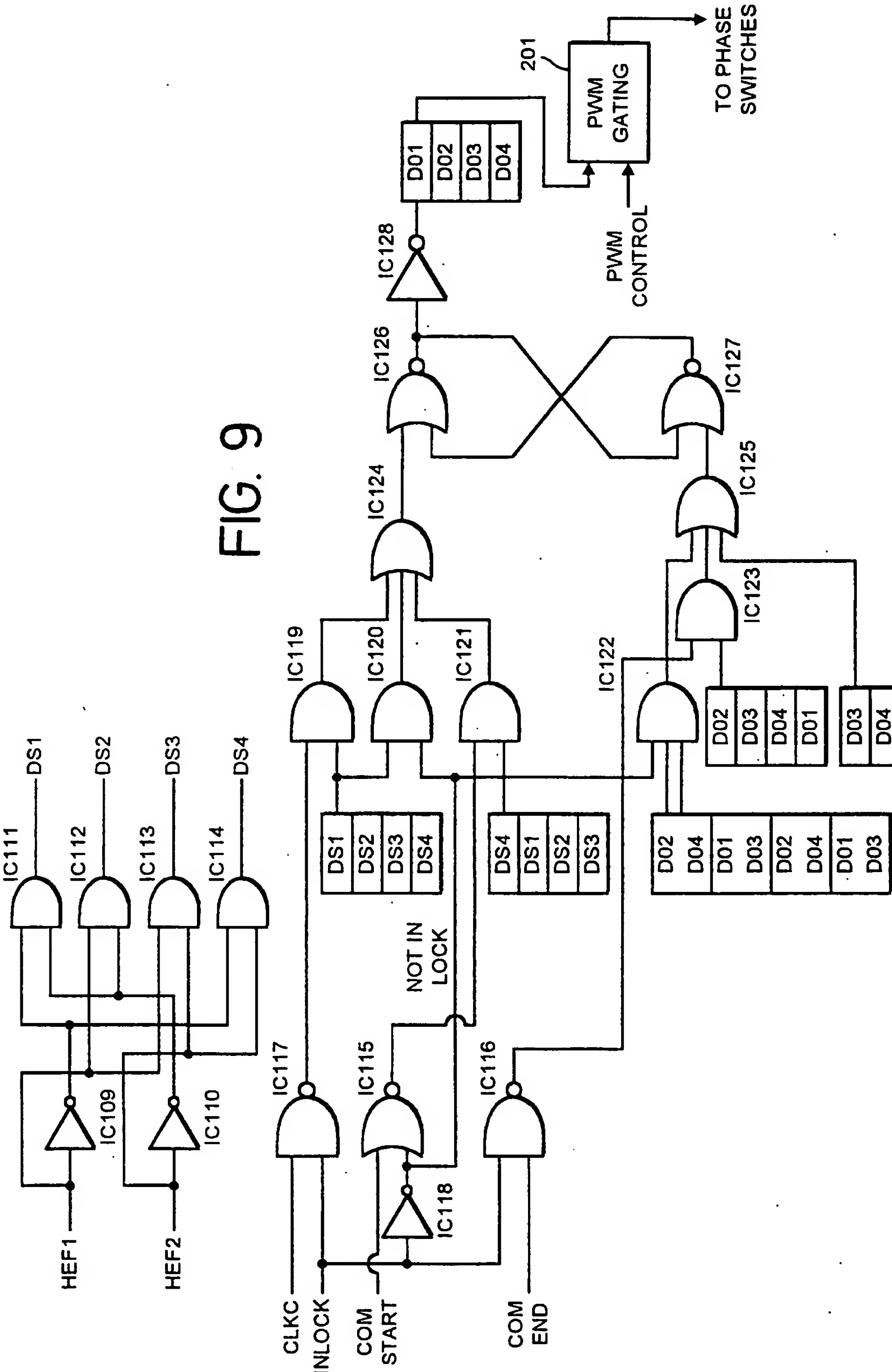

HEF1
HEF2
IC109
IC110
IC111
IC112
IC113
IC114
DS1
DS2
DS3
DS4
CLKC
INLOCK
COM START
COM END
IC115
IC116
IC117
IC118
NOT IN LOCK
IC119
IC120
IC121
IC122
IC123
IC124
IC125
IC126
IC127
IC128
DS1 DS2 DS3 DS4
DS4 DS1 DS2 DS3
D02 D04 D01 D03 D02 D04 D01 D03
D02 D03 D04 D01
D03 D04 D01 D02
D01 D02 D03 D04
PWM CONTROL
PWM GATING
201
TO PHASE SWITCHES

FIG. 9

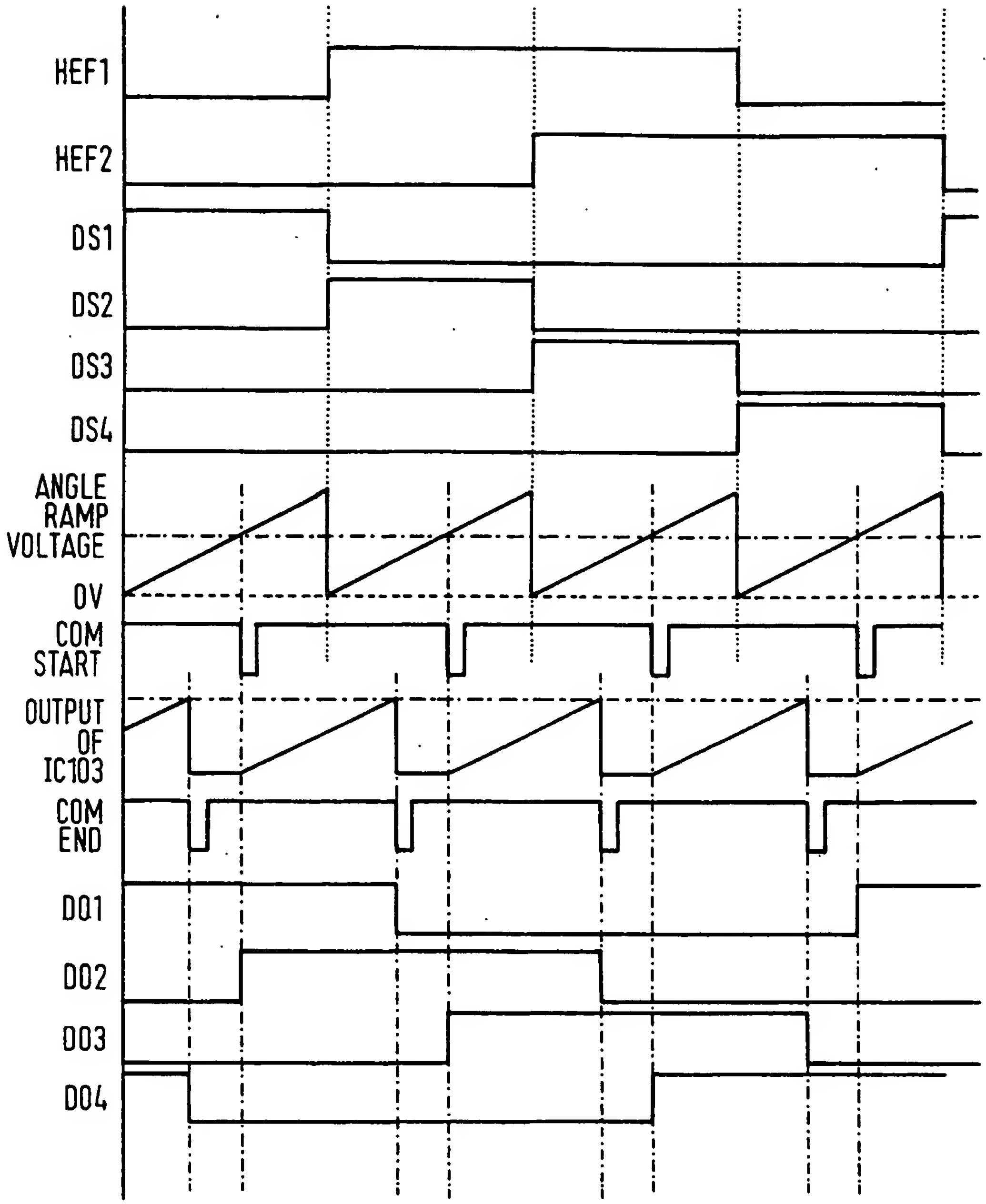

HEF1
HEF2
DS1
DS2
DS3
DS4
ANGLE RAMP VOLTAGE
0V
COM START
OUTPUT OF IC103
COM END
DO1
DO2
DO3
DO4

FIG. 10

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 96/02084

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H02P6/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H02P

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US,A,4 546 293 (PETERSON WILLIAM J ET AL) 8 October 1985 see column 1, line 49 - line 60 see column 6, line 1 - line 47; figure 5	1-4,8,12,13
X	DE,A,38 19 062 (QUICK ROTAN ELEKTROMOTOREN) 7 December 1989 see abstract	1,12,13
X	DE,A,24 03 432 (SIEMENS AG) 31 July 1975 see page 1 - page 2	1,13
X	EP,A,0 505 159 (FUJITSU LTD) 23 September 1992 see column 7, line 28 - column 9, line 30; figure 9A	1-4,12,13

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

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"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

1

Date of the actual completion of the international search	Date of mailing of the international search report
2 December 1996	06.12.96

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax (+31-70) 340-3016	Bourbon, R

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 96/02084

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP,A,0 548 059 (SONY CORP) 23 June 1993 see abstract -----	1-4,13

1

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Information on patent family members

Int 'onal Application No
PCT/GB 96/02084

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
US-A-4546293	08-10-85	DE-A-	3322653	01-03-84
		FR-A-	2532490	02-03-84
		GB-A,B	2126026	14-03-84
		JP-A-	59056880	02-04-84
DE-A-3819062	07-12-89	JP-A-	2036788	06-02-90
DE-A-2403432	31-07-75	CH-A-	577246	30-06-76
		JP-C-	1230045	19-09-84
		JP-A-	50104316	18-08-75
		JP-B-	59003120	23-01-84
EP-A-0505159	23-09-92	IN-A-	172484	28-08-93
		JP-A-	4295294	20-10-92
		US-A-	5298839	29-03-94
EP-A-0548059	23-06-93	JP-A-	1122387	15-05-89
		CA-A-	1292504	26-11-91
		DE-D-	3884137	21-10-93
		DE-T-	3884137	07-04-94
		EP-A-	0316077	17-05-89
		US-A-	4874993	17-10-89